Alternative Fuels from Solid Waste in Egypt

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ABSTRACT

Given the need for alternative sources of energy in Egypt, the energy crisis worldwide, and waste management problems in Egypt, waste-to-energy (WTE) seems to be an optimum solution for both problems: energy and waste disposal. In this research, a comparative study was conducted to investigate the average calorific value of various waste materials from agricultural, industrial, and municipal waste sources including six types of plastics, tires, sawdust, rice straw, rice husk, corn husk, bagasse, and onion leaves. Since biomass pellets are more uniform, and easier to transport and store, the second phase of the study investigated the use of starch, water, and $Ca(OH)_2$ as binders for biomass pellets and their impact on the average calorific value. The final phase investigated emissions produced from the most promising waste materials. The results showed that among the six types of plastics, polypropylene (PP) has given the highest average calorific value, while bagasse had a maximum average calorific value among the five investigated agricultural wastes. Rice straw can also be one of the promising agricultural WTE materials in Egypt because it is abundant in large quantities; same as tires which are widely available and have high average calorific value when compared to fossil fuels like coal and diesel.

Keywords: alternative fuels, waste-to-energy, calorific value, emissions

1. INTRODUCTION

Access to energy nowadays has become more expensive and more environmentally damaging. In Egypt, energy prices for industry have been increasing in the last few years, but this increase has not been drastic because prices remain governmentally regulated. The total consumption of energy in the industrial sector has increased from 17.5-million-ton oil equivalent (mtoe) in 2000/2001 to 27.2 mtoe in 2011/2012, which means an average annual growth rate of 4.1% during that period. Furthermore, the total final energy demand in the industrial sector is expected to increase from about 21 mtoe in 2008 to reach about 41-46 mtoe in 2030 according to the “Mediterranean Energy Perspective (MEP) – Case study of Egypt”. The largest energy demand goes to industry and electricity generation. Industry is divided into subsectors including iron and steel, fertilizers, and cement industry with the remaining industries categorized as “other” and which includes food, textile, etc [1].

Cement industry constitutes one of the most energy-intensive industries. There are two main types of energy used in this industry, which are fuel and electricity. Electricity is used for exhaust fans and grinding mills, while fuel is used for firing the kilns, and drying and pre-heating raw materials. The main fuel for the cement industry is mainly provided by coal, natural gas, and fuel oil. Availability, cost, and environmental constraints are the key factors for choosing between those three fuels. Approximately, 3,000-6,000 MJ of energy is required per ton of clinker produced, and since natural gas is the main source of fuel in Egypt's case. Its specific energy consumption is estimated with 100 m^3 per ton of cement, which is about 5 kg of fuel oil per ton. Egypt's Energy Strategy for 2030 expects that demand for natural gas in the cement industry will increase from about 2.5 billion cubic meter (bcm) in 2008/2009 to be 14 bcm in 2029/2030 [1].

Another problem that Egypt currently faces is the enormous amounts of solid waste that is clearly visible throughout the country and which cause various environmental and health hazards. Most experts agree that this waste can be a hidden treasure for the nation, if it is fully exploited. Indeed, solid waste can be reused, recycled, or even recovered as a source of energy instead of simply being disposed in dumpsters and landfills [2]. However, Egypt suffers from serious problems with respect to its solid waste management (SWM) system. Furthermore, it is predicted that the quantities of MSW will increase from about 20 million ton (MT) of waste in 2013 [3] to more than 30 (MT) in 2025 [4]. Additionally, the agricultural waste, as mentioned above, was estimated in 2012 at 30 million tons. Table (1) shows the average annual amount of waste produced from some major agricultural corps in Egypt [5]. Given the increasing levels of waste production and ongoing problems with waste management, a revolutionary SWM system is desperately needed and one which involves the collection, transportation, and disposal of waste. In order to minimize waste disposal in dumpsites and landfills, waste can be reused, recycled, or converted into energy. Considering the energy crisis, waste-to-energy seems to be the optimum solution for both problems: energy and waste disposal.

Crop	**Cultivated area (feddan)**	**Solid waste generation (tons/feddan)**	**Total (tons)**
Rice	1,507,634	2.1	3,015,000
Maize	1,657,799	1.9	3,150,000
Wheat	2,506,178	2.56	6,415,000
Cotton	535,090	1.6	856,144
Sugar cane	327,215	11.9	3,726,978
Total	6,206,701	-	17,163,122

Table 1 – Annual cultivated areas and agricultural solid waste production for major crops [5]

From here, the objective of this research is to investigate the use of solid waste in Egypt as alternative fuels, including: determining average calorific values of various municipal, agricultural, and industrial solid wastes in Egypt, examining the effect of using different binders on the average calorific value of biomass pellets, and conducting a relative comparison between the amount of pollutant emissions produced from the most promising wastes as mass per unit mass of the burned material. This comparison can be considered as an indicator to the real amount of emissions produced in the field, which would help in assessing the environmental impact of using those alternative fuels, which material should be used in terms of the calorific value and produced emissions, and making decision on mitigation measures that should be taken.

2. METHODOLOGY

This research was divided into three phases. The first phase was conducted to get the calorific value of various solid waste materials from agricultural, municipal, and industrial sources. The selected materials of waste were chosen based on the literature. The agricultural wastes are categorized into two groups: agricultural crop residues (straw, stalks), and agro-industrial crop residues (leaves, kernels, shell, husk). The agricultural related wastes used here were: rice straw, rice husk, bagasse, corn husk, and onion leaves. From literature, corn cobs were examined earlier as an alternative fuel [6], however, corn husk was chosen in this study because it is a waste of no appreciable value to industries. The other wastes from municipal and industrial activities were: tires, various types of plastics, laminated plastics (chips and chocolate packaging bags) and wood residues from industrial activities (sawdust). Plastics included in this research were high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS). The second phase of the study was concerned with the effect of different binders and their percentage on the average calorific value of biomass pellets, while the third phase was carried out to trace emissions produced from the most promising waste materials to be used as an indicator to the emissions resulted and decide on the proper mitigation technologies that should be used. The three phases of this research were conducted on lab scale. The grain size of each waste material is shown in Table 2. It was anticipated that grain size does not influence the material's calorific value. However, rice straw, corn husk, and tires were grouped into two size ranges to make sure that grain size does not affect the average calorific value of waste material. In order to get the moisture content of biomass materials, a sample of each of the six tested biomass materials: rice straw, rice husk, corn husk, onion leaves, bagasse, and sawdust was weighed and then dried in an oven at 105 ˚C until the sample achieved a constant weight (ASTM, 2010). Afterwards, the sample was cooled in a desiccator and then weighed again. The moisture content was calculated on a wet basis by Equation 1:

$$\text{Moisture content (\%)} = \frac{\boldsymbol{wet\ mass\ (g)-dry\ mass(g)}}{\boldsymbol{wet\ mass\ (g)}}\ \boldsymbol{x\ 100}$$

Table 2 - Grain size of the investigated waste materials

Material	**Size range**
Rice straw	63µm - 425µm, 850µm - 1.18mm
Rice husk	106 µm – 1.7mm
Corn husk	63µm - 425µm, 850µm - 1.18mm
Bagasse	63µm - 425µm
Onion leaves	< 710µm

Sawdust	<1.18mm
Tires	63µm - 425µm, 850µm - 1.18mm
Laminated plastics	106µm – 1.7mm
PET	<2.00mm
PP	425µm – 2.00mm
HDPE	106µm – 850µm
PVC	106 µm – 2.00mm
PS	106µm – 1.18mm

To measure the average calorific value of the selected waste materials, an oxygen bomb calorimeter (XRY-1A) was used. The used bomb calorimeter was made and designed as per the National Standard of People's Republic of China GB/T213-2008. A sample of 0.53 g of each material was tested five times and then the average calorific value was calculated. The calorific value of sample is the heat produced when burning a unit mass in the oxygen bomb that contains excessive oxygen (J/g or kJ/kg). From the obtained data, calorific value of the sample was calculated using the following equations (Equation 2, 3):

$$E=\frac{Q1\ M1+40}{\Delta T} \quad (2)$$

Where,

E = Heat capacity (J/˚C), Q_1 = Heat value of standard benzoic acid (26456 J/g), M_1 = Mass of benzoic acid (g), and ΔT = Temperature increase ($T_f - T_i$) in the calorimeter system (˚C)

$$Q=\frac{E\ .\ \Delta T-40}{G} \quad (3)$$

Where,

Q = Heat value of sample (J/g), E = Heat capacity of the instrument (J/˚C), ΔT = Temperature increase ($T_f - T_i$) in the calorimeter system (˚C), and G = mass of sample (g)

In the second phase of this study, the impact of different binders on the calorific value of biomass pellets was investigated. Based on international standards, the moisture content of pellets should be < 10%, and binders' percentage should be ≤ 2% [7] [8]. The moisture content of biomass materials used in this study ranged between 7.0 – 7.3 wt% (wet basis). Mass of 0.53 g for each biomass sample (rice straw, rice husk, corn husk, bagasse, onion leaves, and sawdust) was pelletized using the compressing machine, and all samples were pelletized under the same compression force. Each binder was added in 0, 2, and 4%, and five samples of each material was tested. The same steps for Phase-I were repeated to measure the calorific value of the pellets.

In the third phase of this study, the most promising materials determined from Phase-I were combusted to inspect the approximate emissions produced from those materials relative to each other. For industries that can use those alternative fuels, this would facilitate the process of determining what mitigation and air control technologies should be used to minimize air pollutants and comply with standards. Emissions were detected with a Testo-350 gas flue analyzer.

The obtained concentrations over time from Testo gas analyzer for CO, NO, NO_2, and SO_2 were in ppm, while CO_2 was given in vol%. Those concentrations were then normalized to express the amount of each pollutant as mass per unit mass of the burned material to be compared to each other. In order to be able to get the mass of each pollutant, concentrations were firstly converted from ppm into mg/m^3. The percentage of CO_2 was converted into ppm, as 1% is equivalent to 10,000 ppm. The following equation (Equation 4) was used to convert from ppm to mg/m^3:

$$\text{mg/m}^3 = \frac{ppm \ x \ M}{0.08205 \ x \ T} \qquad (4)$$

where,

M: molecular weight of gas, T: temperature of combustion in Kelvin (˚C+273), and 0.08205: universal gas constant

3. RESULTS AND DISCUSSION

The results show that the highest average calorific values of the selected agricultural waste were obtained from bagasse, then corn husk, which were 17,309 kJ/kg, and 16,911 kJ/kg with standard deviation of ±2.96%, and ±2.38 %, respectively. Comparing both rice straw and rice husk, there was no large difference between the two, however, rice husk gave greater average calorific value of 15,178 kJ/kg and standard deviation of ±2.47%, while rice straw's average calorific value was 14,435 kJ/kg with standard deviation of ±1.59%. Onion leaves' average calorific value was very close to that of rice straw, which was 14,340 kJ/kg with a standard deviation of ±3.32 %. Figure 1 shows the selected five agricultural wastes and their average calorific values.

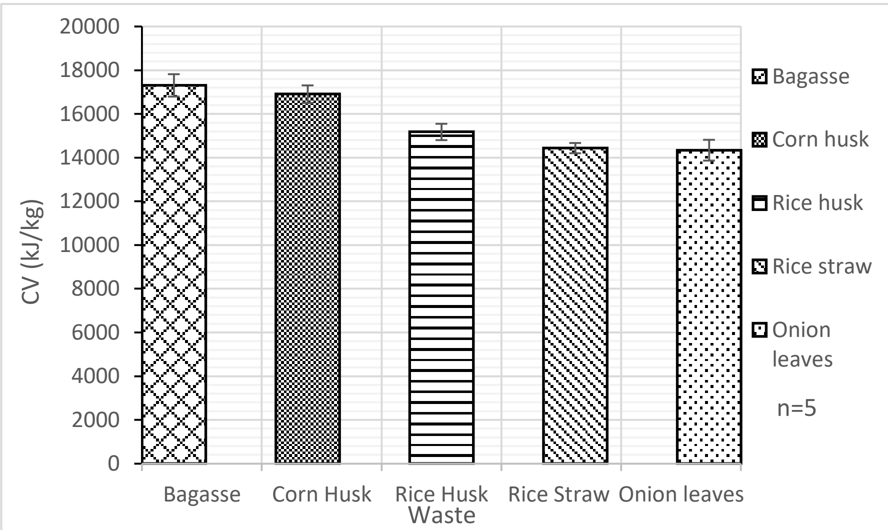
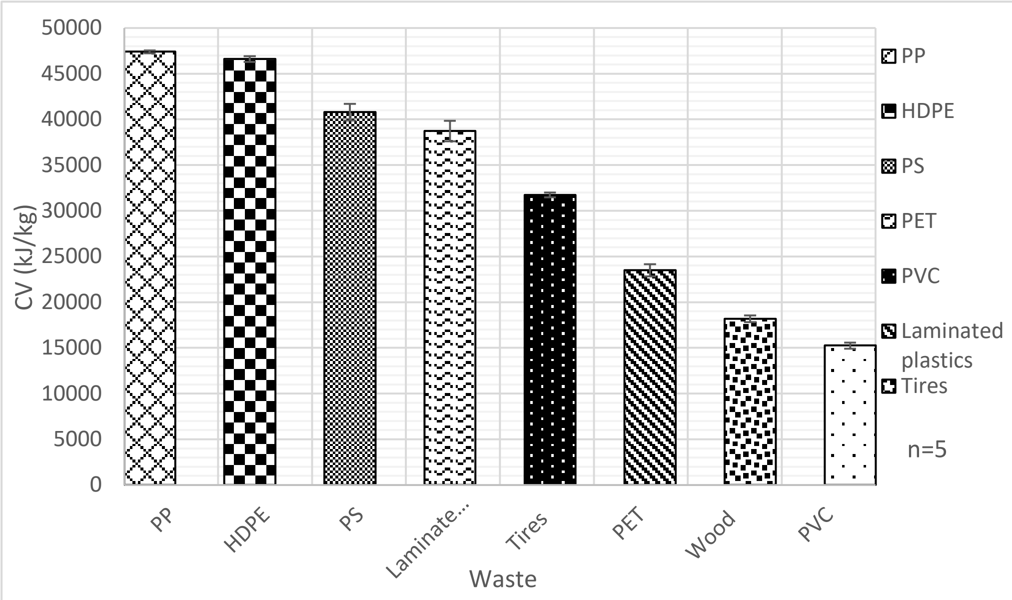


Figure 1 - The average calorific values of the selected agricultural wastes

For industrial and municipal wastes, as presented in Figure 2, PP achieved the highest average calorific value among all the measured plastics with an average calorific value of 47,390 kJ/kg, while PVC gives the least value of 15,245 kJ/kg, with standard deviation of ± 0.33%, and ± 2.09%, respectively. The average calorific value of HDPE is relatively close to PP with average calorific value of 46,609 kJ/kg. The standard deviation of HDPE's average calorific value was ± 0.68%. Another material is laminated plastics that is used widely to manufacture chips and chocolate packaging, and it has an average calorific value of 38,373 kJ/kg with standard deviation



of ± 2.91%, which is even greater than PET and PVC's calorific values of 23,483 and 15,245 kJ/kg, and standard deviation of ± 2.87 and ± 2.09%, respectively. The average calorific value of tires was 31,731 kJ/kg with standard deviation of ± 0.87%, while the sawdust produced by different industries gives average calorific value of 18,177 kJ/kg with ± 2.06% standard deviation. From the results obtained in this phase, it could be highlighted that laminated plastics can be considered as a potential source of energy. It has a relatively high calorific value that is even higher than the calorific value of tires and other types of plastics like PET and PVC.

Figure 2 - The average calorific values of the selected industrial and municipal solid waste materials

The average calorific values obtained using the bomb calorimeter in this study were validated by comparing them with values from literature. As shown in Table 3, the comparison demonstrates that both values were very close, with minor differences. The maximum difference reached about 19.8 % for PVC, while for the rest of the materials it ranged between 0.5-11.9 %. Those differences could be resulted due to many factors such as the source of materials that might accordingly change its physical properties like moisture content of the waste.

The variability in the calorific value of different materials is due to several factors related to the proximate and ultimate analysis of those materials. Proximate analysis determines volatile matter, ash, moisture, and fixed carbon, while ultimate analysis gives the percentage of carbon, hydrogen, nitrogen, and sulphur [9]. As the volatile matter increases and the moisture content decreases, the calorific value of the material increases. Also, the hydrogen to carbon (H/C) ratio is one of the main factors that affect the calorific value of a material; the calorific value increases as the H/C ratio increases [10]. For example, the calorific value of PVC $(C_2H_3Cl)_n$ is much lower than that of PP $(C_3H_6)_n$ because of the fillers used in PVC and the lower number of hydrogen atoms.

Table 3 - Comparison between average calorific values obtained from bomb calorimeter and the literature

Material	CV (kJ/kg) – Bomb calorimeter	CV (kJ/kg) – Literature	Difference %	Reference
PP	47,390	44,000	7.7	(Themelis, Castaldi, Bhatti, & Arsova, 2011)
HDPE	46,609	44,000	5.9	
PS	40,784	41,000	0.5	
PET	23,483	24,000	2.2	
PVC	15,245	19,000	19.8	
Tires	31,731	29,000-36,000	9.4 - 11.9	(Singh, Nimmo, Gibbs, & Williams, 2009)
Sawdust	18,177	20,000	9.1	(Capareda, 2011)
Rice Straw	14,435	15,200	5.0	(Capareda, 2011)
Rice Husk	15,178	15,400	1.4	

Two grain sizes of three materials: rice straw, corn husk, and tires were tested in order to be used as an indicator to ensure that grain size does not have impact on the calorific value of materials. The results in Figure 3 shows that the grain size was unlikely to affect the calorific value of materials. As for rice straw and tires, the difference between both values was less than 1%, while for corn husk it was 1.2%. However, it is speculated that the grain size will more likely to have impact on the combustion behavior, which could not be examined in this study due to some limitations.

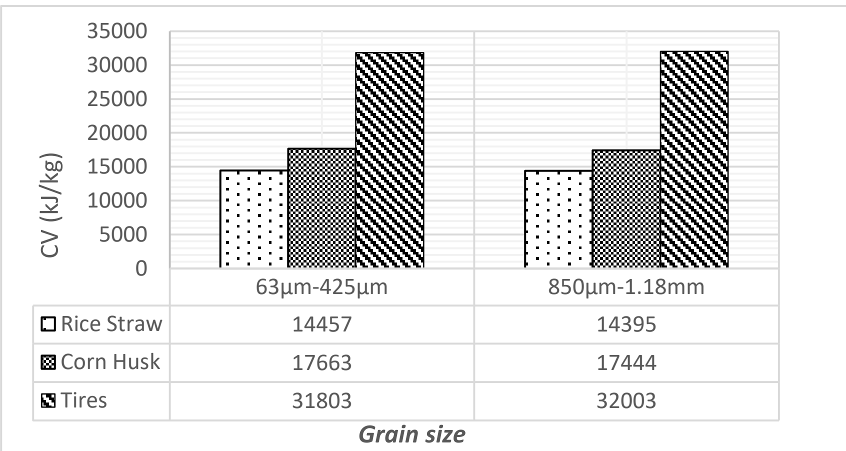


Figure 3 - Effect of Grain size on the calorific value

Pellets can make transportation, storage, and handling easier to manage biomass. Pellets should satisfy certain standards based on the following characteristics: bulk density, mechanical durability, dimensions, ash content, calorific value, moisture content, binding agent/additives percentage and others [14]. However, the focus of this research is to investigate the average calorific value of pellets with different percentages and types of binders. The used binders were water, starch, and calcium hydroxide $Ca(OH)_2$, which were selected based on literature [15] [16]. Each binder was tested at 0, 2, and 4 wt% of biomass.

The results obtained using starch, $Ca(OH)_2$, and water as binders (Table 4) does not significantly affect the average calorific value of the tested biomass: bagasse, rice straw, rice husk, corn husk, onion leaves, and sawdust.

For rice straw, corn husk, and wood (sawdust), it was found that as the percentage of water increased, the average calorific value decreased. However, the reduction was minor within range of 3.3 – 6.3% of the pellet's average calorific value with 0% binder. The minimum decrease of 3.3% took place at 2% water for corn husk, while the maximum decrease of 6.3% occurred at 4% water rice straw. The other biomasses: bagasse, rice husk, and onion leaves did not show an exact trend, however, the changes were also minor and ranged between 0.3 – 6.0%.

For starch, the results obtained acted in a similar trend to bagasse, rice husk, and onion leaves with water as a binder. The differences happened in the average calorific value of the six biomasses were in range of 0.6 – 5.4%, with the maximum at wood with 4% starch, and the minimum at corn husk with 2% starch.

For $Ca(OH)_2$, the average calorific value of rice straw, corn husk and wood pellets decreased with increasing the percentage of $Ca(OH)_2$, same as in water. However, the changes ranged between 1.2 – 13.3%, with the minimum change of 1.2% occurred at rice straw with 2% $Ca(OH)_2$, while the maximum was at wood with 4% $Ca(OH)_2$. The results of remaining wastes: bagasse, rice husk, and onion leaves were also similar to pellets of the same materials with water as a binder. Change in the average calorific value of those materials ranged between 0.6% - 9.6%. The highest change took place in onion leaves pellets with 2% $Ca(OH)_2$ binder, while the lowest difference in calorific value was at 4% $Ca(OH)_2$ bagasse.

The obtained results might have been influenced with some factors that could have resulted in minor errors accordingly. Although it was ensured that the binder had been mixed very well with the biomass sample, there might have been some discrepancies in the sample's homogeneity. Also, the room temperature could also affect the sample's temperature, which could consequently cause those minor changes. However, the results showed that the three binders: starch, water, and $Ca(OH)_2$ did not affect the average calorific value of biomass dramatically, but more research is still needed in this area to examine other properties such as density, mechanical durability, ash content, emissions and others in order to be able to determine the optimum binder to be used.

Table 4 – Calorific values of biomass pellets

Material	Loose Calorific Value (kJ/kg)	Pellets						
		% Binder	Starch		$Ca(OH)_2$		Water	
			Calorific value (kJ/kg)	Standard Deviation %	Calorific value (kJ/kg)	Standard Deviation %	Calorific value (kJ/kg)	Standard Deviation %
Bagasse	17309	0	17263	5.98	17263	5.98	17263	5.98
		2	16750	0.84	17435	3.82	18291	0.88
		4	18163	0.11	17363	1.05	17163	3.41
Rice Straw	14435	0	13864	6.26	13864	6.26	13864	6.26
		2	13493	0.9	13702	2.47	13217	1.75
		4	13621	2.22	13421	3.46	12993	7.00
Rice Husk	15178	0	14635	5.48	14635	5.48	14635	5.48
		2	14364	0.54	14235	2.02	14474	2.86
		4	14935	3.38	14893	2.35	14693	2.75
Corn Husk	16378	0	16378	7.46	16378	7.46	16378	7.46
		2	16278	0.62	15421	7.98	15835	3.06
		4	16206	0.25	15350	3.95	15792	4.22
Onion Leaves	14340	0	14136	0.71	14136	0.71	14136	0.71
		2	14421	4.06	12779	1.69	14588	9.45
		4	14450	0.42	13093	0.62	14226	10.00
Wood	18177	0	18782	0.89	18782	0.89	18782	0.89

		2	18492	2.95	18320	8.6	18106	3.68
		4	17775	0.68	16278	8.07	17980	0.2

From both literature and the abovementioned results obtained from Phase-I, it was found that bagasse is the most promising material among the tested agricultural wastes in terms of the average calorific value, which is 17,309 kJ/kg for bagasse. Furthermore, rice straw can also be used as a potential WTE source instead of open-field burning that causes serious environmental problems due to its availability in large quantities and its average calorific value of 14,435 kJ/kg. On the other hand, polypropylene and tires were selected as the most promising WTE materials from the tested municipal and industrial wastes. Polypropylene was found to have the highest average calorific value among the five investigated plastics with an average calorific value of 47,390 kJ/kg, while tires can also be considered as a promising source of energy because of its abundancy in enormous amounts in addition to the relatively high average calorific value of 31,731 kJ/kg. All selected materials have a satisfying calorific value when compared with some other common fossil fuels like coal, which have a heating value within range of 15,003 – 25,772 kJ/kg. Also, diesel, which is commonly used as a source of energy, has a calorific value of 44,799 kJ/kg that is close to the calorific value of polypropylene as well as other types of plastics [17].

The area under the curve, which is presented as mass of CO per unit mass of rice straw, bagasse, tires, and polypropylene in a minute were 12.56, 19.15, 56.56, and 38.16 g.min/kg, respectively, as shown in Figure 4, which means that tires had the highest value of CO emission, then polypropylene. Also, bagasse emitted CO more than rice straw. The mass of NO per unit mass of rice straw, bagasse, tires and polypropylene were 0.39, 0.59, 0.35, and 0.18 g.min/kg, respectively (Figure 5), meaning that polypropylene had the lowest value of NO, while bagasse produced the highest value, then rice straw. As illustrated in Figure 6, the mass of NO_2 per unit mass of rice straw, bagasse, tires, and polypropylene was 0, 0.012, 0.012, and 0.0016 g.min/kg, respectively. The amount of NO_2 produced from bagasse and tires were almost the same and they gave the maximum value, while rice straw did not emit NO_2 at all. The mass of SO_2 per unit mass of rice straw, bagasse, tires and polypropylene were 0, 0, 2.73, and 0g.min/kg, respectively as demonstrated in Figure 7. From these values, it was observed that tires were the only material that produced SO_2 emissions. However, those zero values in Figure 6 and Figure 7 could have been very small values, not absolute zero, due to the accuracy of the Testo gas analyzer that reached ±10 ppm for NO_2 and ±20 ppm for SO_2. The mass per unit mass of CO_2 for rice straw, bagasse, tires and polypropylene was 552.56, 685.68, 745.6, and 662.64 g.min/kg, respectively as shown in Figure 8. The maximum value of CO_2 was produced from tires, then bagasse. The minimum value was obtained from rice straw.

Mass loss in tires mass, which is the total burned mass minus remaining mass and mass of produced emissions, was the minimum with value of 3% loss, while the maximum mass loss was 28% in polypropylene. For rice straw and bagasse, the mass loss was 16%, and 25%, respectively. Those mass losses may have affected the obtained results. According to Irfan et al. (2014), it was reported that rice straw reached a mass loss of 19% in a previous study, although other materials normally have mass losses of 10%. The authors also stated that variations in combustion conditions and fuel properties could result in high degree of uncertainty and rough estimates [18].

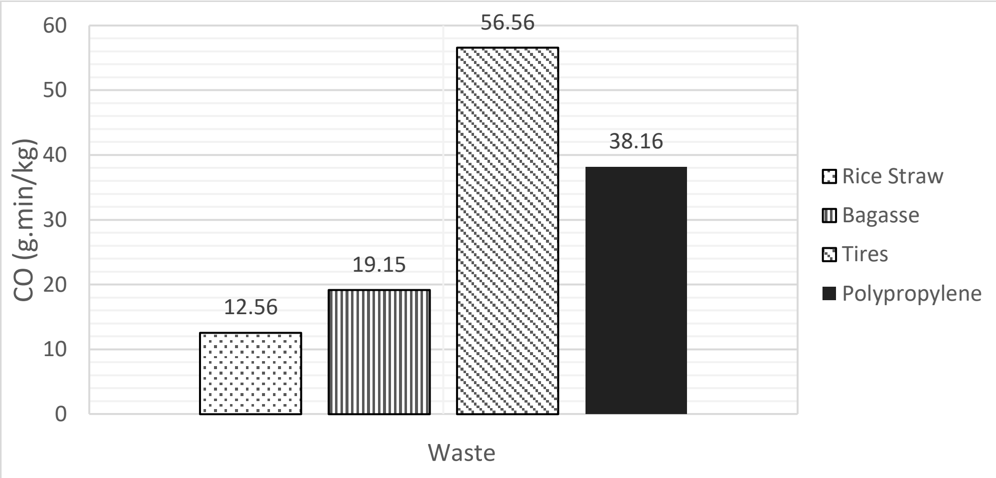
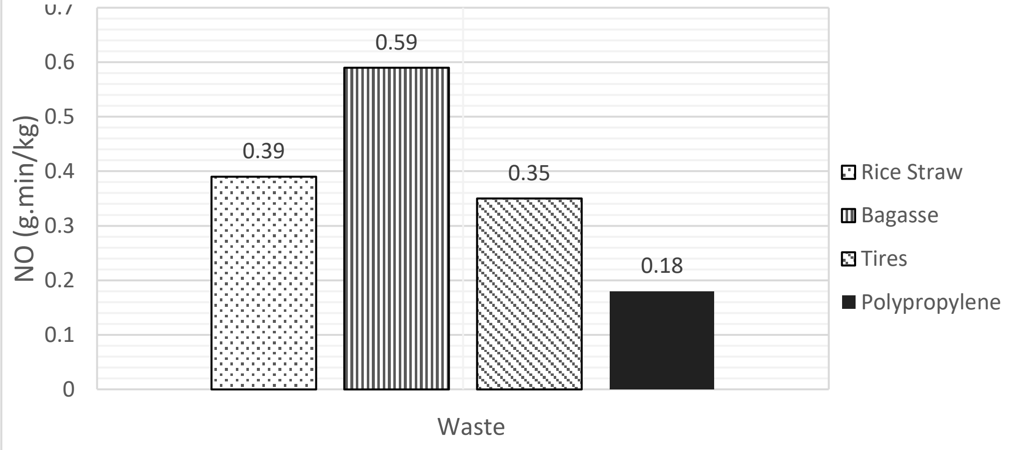


Figure 5 - NO pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

Figure 6 – NO_2 pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene



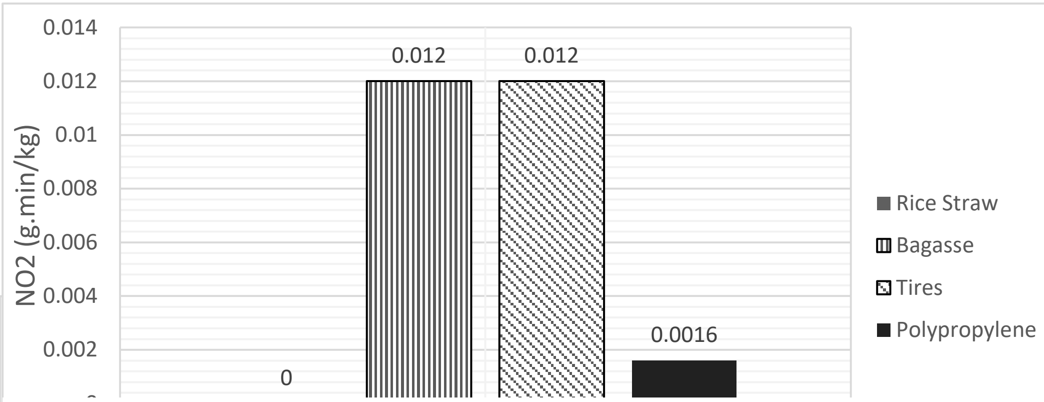


Figure 7 - SO_2 pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

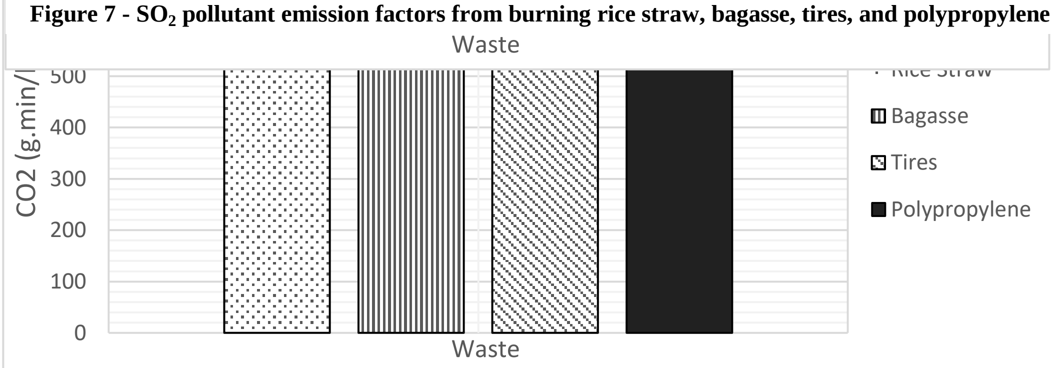


Figure 8 - CO_2 pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

Various factors could have impacted the combustion process, which may have resulted in discrepancies in values of emissions, such as the mass loss, and the inability to measure all emissions with the Testo gas analyzer. Also, those values can differ from one test to another even for the same material due to differences in the combustion conditions, and in chemical composition of C, S, and N of the burned material, in addition to the moisture content, as discussed by Irfan et al. [18]. Another issue that should be taken into consideration is that the Testo gas analyzer gives rough estimation for emissions that enabled conducting a comparative study between different wastes, and not accurate values.

4. CONCLUSION

This research work can be considered as a primary investigation to the use of different solid waste materials in Egypt as alternative fuels. Such alternative fuels can be a clean source of energy and an optimum solution for energy crisis and depletion of fossil fuels. Furthermore, waste-to-energy can contribute in solving the waste management problem in Egypt. The main findings of this study are summarized in the following points:

- All used wastes have a reasonable calorific value when compared to coal's calorific value, which is 15,003-25,772 kJ/kg. The minimum calorific value was provided by rice straw, and the maximum calorific value among agricultural wastes was bagasse. The highest calorific value among all measured wastes was given by polypropylene.
- Laminated plastics could be a potential waste-to-energy material that has a relatively high calorific value.
- The three binders: starch, water, and $Ca(OH)_2$, did not have a significant impact on the calorific value of the tested biomasses: rice straw, rice husk, corn husk, bagasse, onion leaves, and wood (sawdust), when added in 0, 2, and 4%.
- The mass of CO and CO_2 per unit mass of tires were the maximum among the four combusted materials of rice straw, bagasse, tires, and polypropylene. The lowest values of CO, and CO_2 were produced by rice straw. Bagasse had the highest mass of NO per unit mass of bagasse, and polypropylene had the lowest. The mass of NO_2 per unit mass of bagasse and tires were the highest and were almost the same. SO_2 mass per unit mass of tires was the highest value among the four selected materials, while rice straw, bagasse, and polypropylene did not produce SO;$_2$.

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